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Aeolus-2: Status of pre-development activities

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Abstract: The European Space Agency's (ESA) Aeolus satellite was launched on 22 August 2018 from Centre Spatial Guyanais in Kourou, French Guyana. The Atmospheric LAser Doppler Instrument (ALADIN), the sole payload on Aeolus, was the world's first spaceborne Doppler Wind Lidar (DWL), providing profiles of horizontal line-of-sight (HLOS) wind retrievals to be used as Numerical Weather Prediction (NWP) model input to improve short to medium range forecasts [1]. Aeolus data has been extensively analysed by a number of meteorological centres and found to have a positive impact on NWP forecasts, particularly in the tropics and polar regions [2]. These positive results, along with the successful in-orbit demonstration of the measurement concept and associated technologies utilized on Aeolus, resulted in a statement of interest from EUMETSAT in a future operational DWL mission in the 2030 to mid-2040s timeframe and a request to ESA to carry out the necessary pre-development activities for such a mission.

1. Introduction

Despite the positive impacts on NWP reported above, a number of open issues on the ALADIN instrument were identified which are required to be resolved in any future DWL mission [3]. The initial atmospheric return signal levels were lower than expected by a factor of around two, causing an increase of the random error for the wind measurements. The UV energy output of the first flight laser (nominal, FM-A) at the beginning of operation was lower than expected from ground measurements by around 20% (65mJ versus 80mJ) and showed a continual monotonic degradation in output with time of operation, of around 40% in 9 months, associated with a gradual misalignment of the master oscillator (MO). The second flight laser (redundant, FM-B) had much improved performance with around 70mJ output energy at the beginning of operations and has remained over 60mJ over 3 years operations. Towards the end of Aeolus operations, the laser energy was increased, in steps, eventually reaching 180mJ. Nevertheless, there has been an important continuous degradation of the atmospheric return signal (not associated with the laser output energy) from the beginning of operations of the second flight laser. This led to the decision to switch on the first flight laser in October 2022. This operation was successful as the initial transmission could be recovered, thereby further extending the mission lifetime to almost 4.5 years compared to the initial mission lifetime of 3 years.

As both the UV energy reduction of the first flight laser during operations and the evolving return signal at constant laser energy were associated with long term evolutions of the laser beam pointing, it was deemed necessary to improve the overall long term stability of the transmitters (which also introduces an evolution in the measurement bias which needs to be corrected) for a follow-on mission. The atmospheric path degradation observed with the second flight laser can only be partially explained by beam misalignments, and there is an additional contribution due to radiometric losses within the optical emission path of the instrument i.e. between laser output and the telescope. This loss, which could be due to long term Laser-Induced Contamination (LIC), Laser-Induced Damage (LID), or the darkening of optics due to activation of colour centres, was one of the major drivers to move from a monostatic (transceiver) design to a bi-static design to separate the emission path (high fluence) and the receiver path, increasing the robustness of the instrument.

2. Aeolus-2 new challenges

The initial inputs from EUMETSAT defined a follow-on mission for two satellites with a 10-15 year lifetime with a proposed launch of the first satellite in 2031, meaning a minimum lifetime of 5.5 years for each spacecraft and a relatively short development timescale for the first satellite compared to previous developments of instruments with high power lasers. This 5.5 years lifetime should be compared to the 3 years lifetime of Aladin. This increase in lifetime has important consequences for the follow-on instrument. Firstly (and also as part of the mitigation for the initial low atmospheric return signal levels on ALADIN), the laser UV energy output needs to be increased from the 60-70mJ on Aladin to 150 mJ. It was assessed that the current laser technologies can be scaled to attain these higher UV energies. As Aeolus-2 will be an operational mission there is an increased need for design robustness and availability of the satellite to produce meteorological data. All this means that calibration and other time allocated to tuning the instrument shall be reduced as much as possible. The pre-developments initiated in this early stage of the mission have as the objective to de-risk as much as possible the technology while ensuring a schedule compatible with the mission timeframe.

The bi-static configuration implies a larger structure to accommodate two independent emission paths (Tx): this will give a complete redundancy of the transmitter optical path with no risk to damage the receiver path (Rx) that is now completely independent. Other challenges highlighted during the instrument study related to the bi-static configuration are the mass increase (also linked to WFE correction in the telescope architecture) and a better Line-of-Sight stability control.

Figure 1 shows the optical sketch of the instrument. The separation of the transmitter path from the receiver path requires the usage of a co-alignment system that maintain both Tx and Rx aligned over mid-term scale to avoid degrading instrument performance.

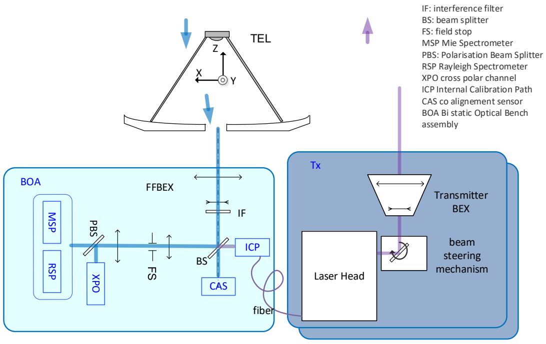

Figure 1. Aeolus-2 instrument optical schematic

For that purpose, a co-alignment sensor is placed on the receiver which monitors the beam atmospheric echo Line of Sight (LoS) depointing which is corrected by a beam steering mechanism. This technique is inherited from ATLID Lidar which is also bi-static design [4].

3. Pre-development status

A set of pre-development activities have been launched to improve the Technology Readiness Levels (TRLs) and de-risk some of the major elements of the instrument like the laser transmitter, beam expander, beam steering mirror (BSM), Accumulation CCD (ACCD) and spectrometers. This section will focus on the progress and status of the main pre-development activities carried out to secure, at breadboard and engineering model level, the main performances needed for the success of this mission.

3.1. Laser transmitter

The laser transmitters are the most critical sub-systems of the instrument, therefore two laser pre-developments have been initiated to mitigate technical and development risks. These developments make use of the heritage from European space Lidar developments. Leonardo SpA, Italy, has developed and qualified the Aeolus ALADIN and EarthCARE ATLID laser transmitters. The Fraunhofer Institute of Laser Technology (ILT) together with Airbus Defence and Space (ADS) GmbH have developed an EQM demonstrator, called FULAS, for ESA and are currently developing the flight model of the MERLIN laser transmitter.

The objective of the pre-developments is to develop an Engineering Model (EM) of the laser head and verify by test the critical functions and performance. The activities are aimed at resolving the issues encountered in-orbit on Aeolus, drawing on the lessons learned from the previous transmitter developments as well as adapting the laser design to meet the requirements for the Aeolus Follow-On mission, in particular targeting laser pulse energy of 150mJ in the UV spectral range.

Key design drivers for the developments are derived from a number of lessons learned from both ALADIN and ATLID developments. In particular:

- the laser shall be in a sealed, pressurized housing (>1atm) containing a partial pressure of oxygen sufficient to prevent Laser-Induced Contamination (LIC);

- minimise changes of the thermal conductance of the thermal interfaces of thermally dissipative units such as amplifiers to avoid thermo-mechanical instabilities;

- minimise risk for Laser-Induced Damage (LID). This implies that while the laser power is scaled up, the laser beam cross section is increased to keep same laser beam fluence on optics;

- minimise risk of LIC with minimization of organic materials used inside the laser;

- implementing an in-flight beam monitoring to have real-time measurements of fluence and be able to react on high fluence event to prevent catastrophic damage in the transmission path.

Both laser suppliers have demonstrated during the pre-development that the required level of UV energy at breadboard level could be achieved. Having different design solutions for the two lasers present advantages and disadvantages. The laser supplier for Aeolus-2 is planned to be selected in April 2024.

3.2. Accumulation CCD

The detector is a custom charge-coupled device developed by Teledyne e2v in the UK, known as the Accumulation CCD or ACCD. The ACCD for Aeolus-2 builds upon the heritage of the design used in the ALADIN instrument, while offering increased capability. The detector images the incoming laser signal and through a series of pixel transfers, the ACCD stores (or accumulates) on chip an atmospheric column profile that has been averaged over the desired number of laser pulses. The vertical resolution of the column profile is determined by the number of range bins (storage pixels) of the ACCD. The key features of the ACCD that help to meet the demanding requirements of the instrument are noiseless charge transfer and accumulation (in effect, averaging), the high-speed transfer of the image to the range bins and the ability to read out at relatively slow speed (and hence low noise) the previous atmospheric column sample data during the acquisition of the current one.

The new detector design incorporates a larger image area, higher vertical resolution and a dedicated image read mode. A number of features to mitigate issues in the previous design have also been implemented. These relate mostly to the hot-pixels that appeared during ALADIN lifetime [5] and include changes to the readout-path to reduce the number of high-speed clocks, and physical layout amendments.

For the pre-development activity, Te2v have designed three new variants. The first two include all the new features and differ only in the number of vertical range bins, either 66 or 132 (compared to 24 in the original ACCD design). The third variant is an updated version of the original ACCD, including the larger image area and the increased number of range bins (66). This device will allow for verification of the mitigation features introduced into the other two variants and to act as a back-up.

The ACCD pre-development is nearing completion with final testing of the new device variants underway.

3.3. EBEX and BSM

The Emission Beam Expander (EBEX), consisting of a sealed and pressurised housing used to expand the high energy laser beam exiting the laser transmitter. The housing also includes a tilting mechanism which allows to co-align the emitted beam toward the reception path. A large beam expansion is required, leading to diameters up to 120mm at the exit of the unit, in order to minimise the output divergence. The critical technologies to be used in the EBEX design shall provide: very stable mounting of large lenses; low Wave Front Error

(WFE); optical coatings qualified for high laser energy fluence; and hermetic sealing for a large volume housing to allow pressurisation of the unit and minimise the risk of LIC. Currently two parallel studies are undertaken by OHB (Germany) and SENER (Spain).

The Beam Steering Assembly (BSA) is composed by the Beam Steering Mechanism (BSM), the BSME (Beam Steering Mechanism Electronics), the BSMFE (Beam Steering Mechanism Front End electronics), if any, and the BSMH (Beam Steering Mechanism Harness) connecting the BSM and the BSME. The parallel pre-developments are developed under CSEM (Switzerland) and OHB (Germany) responsibility, respectively.

The Aeolus-2 bistatic mechanical architecture is quite different from the ATLID architecture. In particular, the BSM is now part of the EBEX cavity, which has several consequences:

- For EBEX, more electrical connections needed for BSM; potentially more sources of contamination;
- For BSM, larger mirror, while still managing a stringent WFE error.

3.4. Spectrometers

Recent studies identified that the implementation of a new spectrometer design and manufacturing processes in the Aeolus-2 bi-static architecture could address stringent bias performance requirements and de-risk critical failure points. Preliminary simulations indicate that an alternate design for the Rayleigh channel spectrometer, based on a Double field compensated Michelson Interferometer (DMI) architecture, significantly reduces sensitivity to angular misalignments. If confirmed, this new design would potentially improve the bias performance at Level 1b. Given that the DMI architecture has lower heritage compared to the Aeolus baseline, a dedicated pre-development has been initiated to increase its TRL and to demonstrate its performance through breadboarding and testing. Drawing from lessons learned during Aeolus, improved optical bonding and glass polishing in the Mie channel spectrometer is central to mitigating risk. The two parallel activities are on-going with TAS (Switzerland) and STI (Germany).

EBEX, BSM and spectrometers pre-developments are parallel activities with different Industries. They are all in the Design Key Point phase going towards the Detailed Design phase. Due to the competitive nature of those pre-developments, no design details can be shared.

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